

# NARROW AND WIDE PULSE EVALUATION OF SILICON CARBIDE SGTO MODULES

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## Abstract

Silicon carbide Super-gate turn-off thyristors (SGTOs) are currently being pursued by the Army as a substitution for present silicon-based, pulsed-power switches. The solid-state modules discussed in this paper were designed and fabricated by Silicon Power and Cree, packaged by Arkansas Power Electronics, and evaluated at the Army Research Laboratory. The module consisted of four SiC GTO die that were packaged implementing ThinPak technology. The die size for each switch in the module was 7.76 mm x 7.76 mm with a total active area of 2.4 cm<sup>2</sup>. Several modules were delivered to the Army Research Lab for pulse switching evaluations. The device characteristics examined from the pulse evaluation were maximum peak current capability, 1000-pulse reliability switching, action, current rise time rate, and current sharing within the module. An update on the module's performance since the pulse work presented at the 2010 Power Modulator Conference is highlighted in this paper. The repetitive wide-pulse switching of the SiC module resulted in a peak current pulse of 5 kA, which corresponds to an action ( $I^2t$ ) of  $1.3 \times 10^4$  A<sup>2</sup>s. The narrow-pulse evaluation of the SGTO module utilized a pulse forming network with low inductance to obtain very high rate of current rise (dI/dt). The narrow-pulse performance obtained for the SiC module was a peak current pulse of 8 kA with a base pulse-width of 170 µs, which corresponds to an action rate of  $5.0 \times 10^3$  A<sup>2</sup>s and a dI/dt of 720 A/µs. This paper also highlights the comparison of the pulse output characteristics of the SiC module to a Si SGTO with similar mesa area.

## I. INTRODUCTION

The Army's desire for compact, light-weight, high power-dense switches on vehicle-mounted pulsed power

platforms has led to the investigation of advanced wide bandgap semiconductor materials such as silicon carbide. The advantages of solid-state switches over plasma-type switches include longer lifetime, increased durability, high repetition rate, and enhanced reliability.

Silicon carbide offers several material advantages over its counterpart silicon such as high critical field, fast switching and recovery time, great thermal conductivity, and large elastic modulus making it favorable for pulse switching systems and applications [1, 2]. Utilizing SiC would increase both current and power densities, improve dI/dt and dV/dt capabilities, reduce recovery time, and minimize switching losses in various pulsed power and power electronic systems. Furthermore, a significant reduction in the volume and weight of pulsed power systems can be realized implementing SiC GTOs, thereby minimizing the thermal requirements to cool various pulsed power systems. To achieve the highest performance with SiC power devices, new packaging techniques will be required. With the continuing improvements in material defect density, carrier lifetime, and fabrication process, SiC GTOs are on pace to becoming commercialized in the near future.

The U.S. Army Research Lab has evaluated single die SiC SGTOs under various pulsed conditions. Silicon carbide has shown at wide pulse-widths condition (1-ms base-width) current capabilities with up to 1.5 times higher current density and 2.5 times higher action compared to similar silicon devices based on previous research done at ARL [3]. Furthermore, silicon carbide SGTOs show lower voltage drop at high current densities compared to silicon GTOs, which leads to lower losses in high-power systems. Silicon carbide's high current density pulse capabilities and potential for 10-20 kV forward voltage blocking will allow for fewer parallel and series switches and an overall reduction in weight and

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<b>14. ABSTRACT</b> <p>Silicon carbide Super-gate turn-off thyristors (SGTOs) are currently being pursued by the Army as a substitution for present silicon-based, pulsed-power switches. The solid-state modules discussed in this paper were designed and fabricated by Silicon Power and Cree, packaged by Arkansas Power Electronics, and evaluated at the Army Research Laboratory. The module consisted of four SiC GTO die that were packaged implementing Thinpak technology. The die size for each switch in the module was 7.76 mm x 7.76 mm with a total active area of 2.4 cm<sup>2</sup>. Several modules were delivered to the Army Research Lab for pulse switching evaluations. The device characteristics examined from the pulse evaluation were maximum peak current capability, 1000-pulse reliability switching, action, current rise time rate, and current sharing within the module. An update on the modules performance since the pulse work presented at the 2010 Power Modulator Conference is highlighted in this paper. The repetitive wide-pulse switching of the SiC module resulted in a peak current pulse of 5 kA, which corresponds to an action (I<sub>2t</sub>) of 1.3 x 10<sup>4</sup> A<sup>2</sup>s. The narrow-pulse evaluation of the SGTO module utilized a pulse forming network with low inductance to obtain very high rate of current rise (dI/dt). The narrow-pulse performance obtained for the SiC module was a peak current pulse of 8 kA with a base pulse-width of 170 ns, which corresponds to an action rate of 5.0 x 10<sup>3</sup> A<sup>2</sup>s and a dI/dt of 720 A/ns. This paper also highlights the comparison of the pulse output characteristics of the SiC module to a Si SGTO with similar mesa area.</p>		
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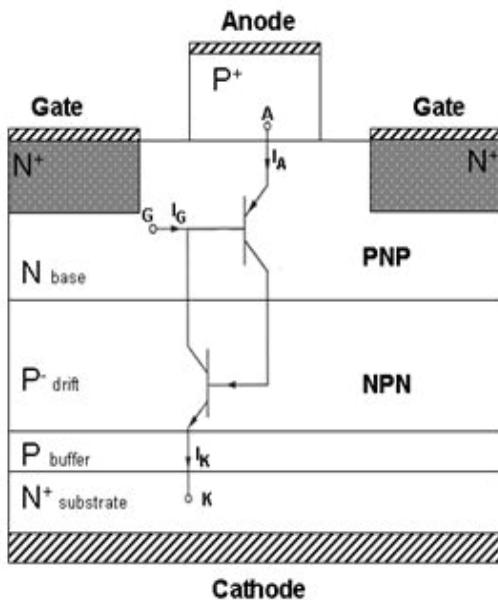
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volume for Army pulsed power systems [4]. Continual improvements in the SGTOs will enable power-dense, reliable performance for both wide and narrow pulse applications, and these switches will become critical components for Army vehicular platforms. This paper includes analysis on the module's narrow and wide-pulse capabilities evaluated since the pulse work presented at the 2010 Power Modulator Conference.

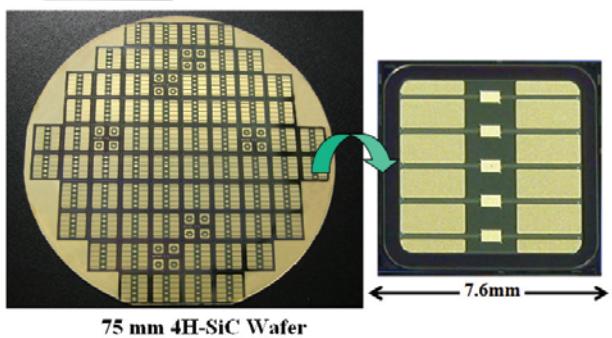
## II. MODULE DESIGN AND PACKAGING

### A. SiC SGTO Structure

The silicon carbide SGTOs of this study were designed by Silicon Power and Cree, fabricated by Cree, and packaged into modules by Arkansas Power Electronics. This solid-state device has a footprint of  $0.6 \text{ cm}^2$  and a central active area of  $0.36 \text{ cm}^2$ . The SiC device layout is a *pnpn* structure as illustrated in Fig. 1 and was inverted and fabricated on a heavily doped n-type 4H-SiC substrate. The SiC device is inverted for better conduction in the on-state. P-type acceptor impurities in SiC due to partial ionization make it highly difficult to obtain good conductivity using p-type SiC substrate. A multiple-zone JTE and a  $60 \mu\text{m}$  thick blocking epi-layer allow for forward voltage blocking beyond 5 kV [5].



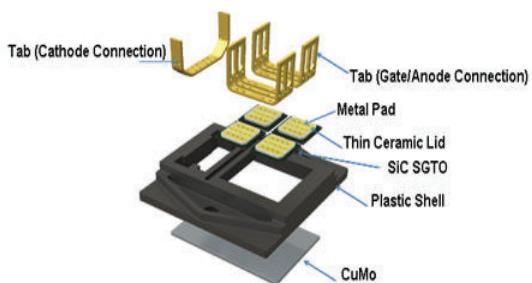
**Figure 1.** PNPN structure and cross section view of SiC SGTO [6].



**Figure 2.** Images of SGTO wafer and close-up of single die. Gold anode and gate pads are visible on the surface of the chip

### B. Module Packaging

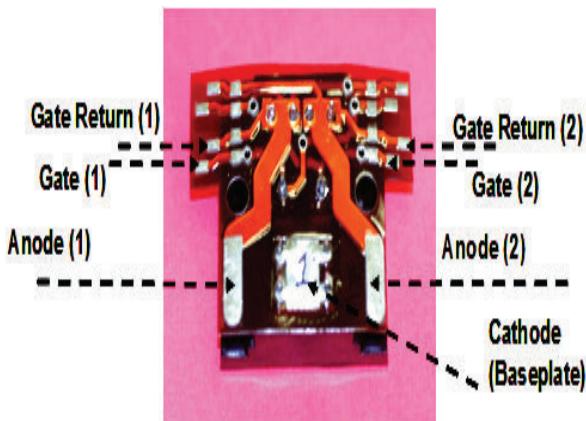
The packaging design for the module utilizes ThinPak technology. ThinPak, as illustrated in Fig. 3 is a solder assembly for power solid state devices that uses patterned metallized ceramic lids to mate with the device electrodes through metallized vias. The benefits of utilizing ThinPak package technology include minimum stray inductance and resistance (no wire-bonds), as well as minimum package volume, weight, and size, which reduces cost [7]. ThinPak technology also improves die electrical and mechanical reliability and thermal cycling capability [8]. The overall dimensions for the SiC module are  $3.5 \text{ cm} \times 3.6 \text{ cm} \times 0.8 \text{ cm}$ . A gold-tin die attach connects the backsides (cathodes) of the die to a copper-moly baseplate. The ThinPak lid replaces wire-bonds and connects to the anode and gate pads. The module's plastic shell is filled with epoxy for high voltage blocking. Copper tabs extend from the ThinPak package for external connection of the module to the pulse power circuit.



**Figure 3.** Image of ThinPak packaging of SiC SGTO—courtesy of SPCO [6].

The arrangement of the devices into two columns determined the bussing of the gate and anode tabs in pairs. The maximum controllable current that these devices can turn-off without failure is dependent on the breakdown voltage of the gate-anode region ( $V_{GA}$ ). The primary factors that affect the gate-anode voltage breakdown are material defects and surface passivation [1]. The gate-

anode voltage breakdown of the total module is dependent on the device with the lowest reverse gate breakdown. Printed circuit boards are connected to the ThinPak to unite the gates and anodes of the four SGTOs together. Fig. 4 displays the assembly of the SiC module incorporating printed circuit boards. The printed circuit board layout allowed for the evaluation of current sharing within the module due to the separation of the anode and gate traces for the two columns. The modules assembled for this study were the first of their kind. Challenges were found and resolved in uniformly aligning the small gate and anode pins and avoiding solder flow in the tight spaces between the individual devices.

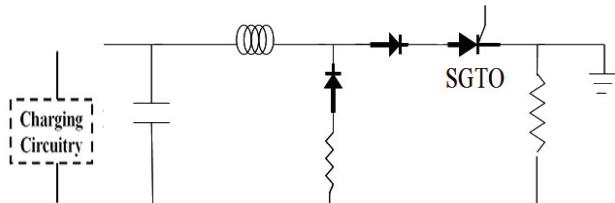


**Figure 4.** Printed circuit board assembly with SiC SGTO module [6]

### III. MODULE EVALUATION

#### A. Wide-pulse Evaluation

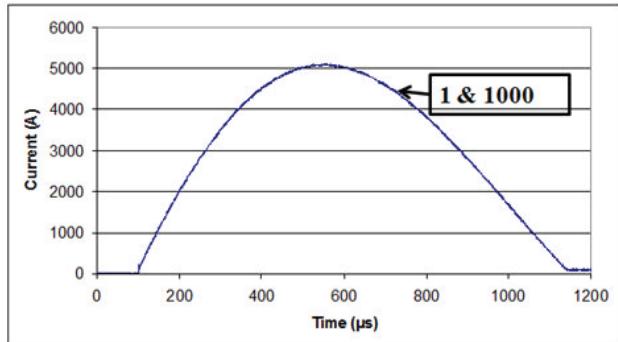
The first evaluation implemented in this research was to determine the switching capabilities of the SiC SGTO module under a half sinusoidal, 1-ms wide-pulse condition. Key parameters that were investigated in this evaluation were peak current repeatability, forward voltage drop, current sharing between parallel SGTOs, and action rate. The wide-pulse circuit consists of a high-energy capacitor bank, a custom made in-house inductor, and a high-energy, low-resistance load. Diodes are used to clamp negatively ringing currents and voltages and to create a symmetrical switching unit (Fig. 5).



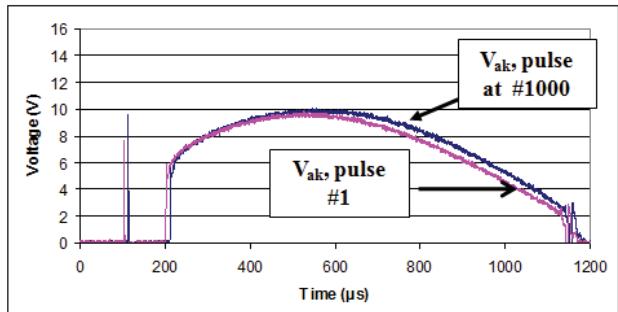
**Figure 5.** Wide-pulse evaluation circuit

To find the peak current rating of the SGTO under wide-pulse conditions, current was slowly increased by intervals of 100 amps. When the anode current approached a maximum level, the forward voltage drop would increase drastically due to current crowding after each subsequent pulse. This resulted in extra heating within the device and would lead to catastrophic failure if device endured continual pulsing at the maximum current rate. Once a safe, repeatable current was determined for each device, one thousand low duty cycle shots were programmed utilizing fifteen-second gaps between switching events. After the pulse evaluation was completed, post-stress static characterization was implemented on the module to assess any device performance degradation.

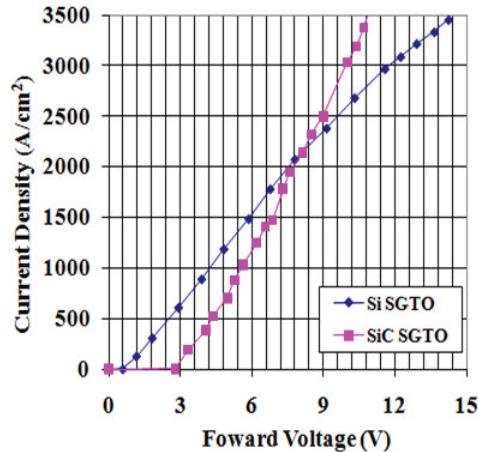
Fig. 6 displays the wide pulse performance of SiC SGTO module. This module endured greater than 1000 pulses at a peak current level of 5 kA with a pulse-width of 1-ms. The action rate at this peak current level was calculated to be  $1.3 \times 10^4 \text{ A}^2\text{s}$  with a current rise rate of  $10 \text{ A}/\mu\text{s}$ . There was a slight increase in the forward voltage drop as illustrated in Fig. 7. However, the forward voltage remained stable throughout the 1000 pulses that the switch endured. The pulsed I-V curve comparison of a  $3.5 \text{ cm}^2$  Si SGTO and the SiC module is displayed in Fig. 8. The Si and SiC I-V curves crossed at about  $2.0 \text{ kA/cm}^2$  and the difference in the forward voltage drop ( $\Delta V=4 \text{ V}$ ) at  $3.5 \text{ kA/cm}^2$  for both devices clearly shows the superiority of SiC at high current density levels.



**Figure 6.** Repeatable wide-pulse peak current of SiC SGTO module. Overlay of pulse 1 and 1000.



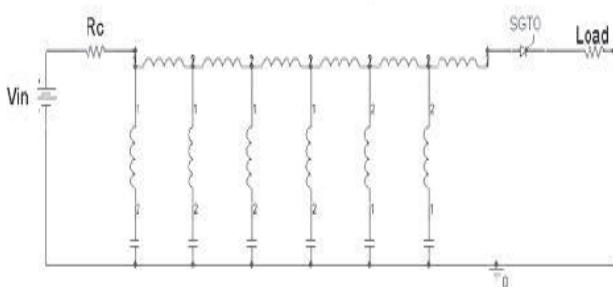
**Figure 7.** Anode voltage drops of SiC GTO module after 1000 pulses.



**Figure 8.** Wide-pulse I-V curves for Si and SiC SGTOs, showing SiC having a lower voltage drop at higher current density

#### B. Narrow-pulse Evaluation

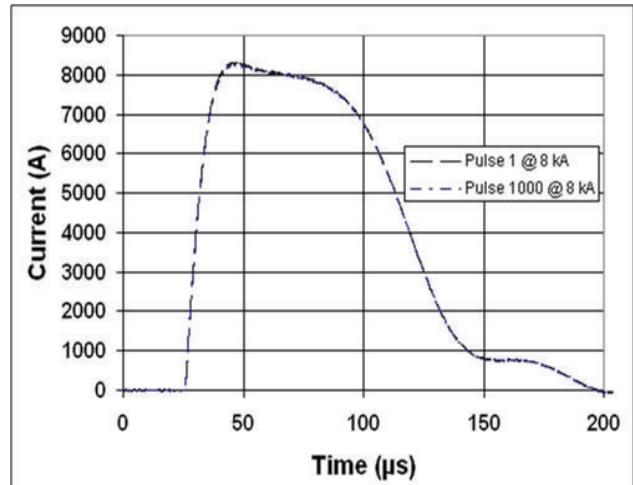
The narrow pulse analysis of the SiC module was done utilizing a pulsed forming network (PFN) as illustrated in Fig. 9. The PFN had total inductance of 100 nH and a total capacitance of 1750  $\mu$ F which enabled fast current rise times ( $dI/dt$ ) of 10  $\mu$ s at pulse-widths less than 200  $\mu$ s when the charge capacitors were discharged by the device under test (SiC SGTO modules). Under narrow-pulse condition, current was slowly increased by intervals of 400 amps until a maximum peak current was reached.



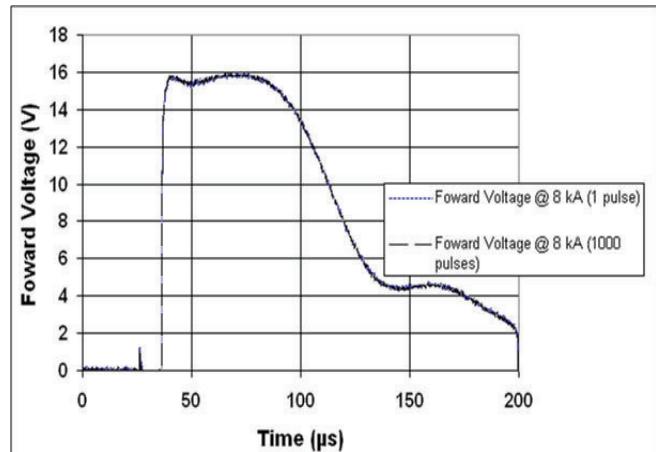
**Figure 9.** Narrow-pulse evaluation circuit utilizing PFN topology

The maximum peak current indication for the module during the narrow pulse evaluation was the rampant increase in forward voltage after every subsequent maximum current pulse. This phenomenon was an indication that the module was on the verge of thermal runaway. Fig. 10 portrays the stable and reliable pulsing of the GTO module at 8 kA with a pulse-width of 170  $\mu$ s. As illustrated in Fig. 11, the module was successfully pulsed 1000 times without any deviation of the forward voltage. The peak current density at 8 kA was 5.6  $\text{kA}/\text{cm}^2$

with a current rise of 720 A/ $\mu$ s and an action rate of  $5.0 \times 10^3 \text{ A}^2/\text{s}$ .

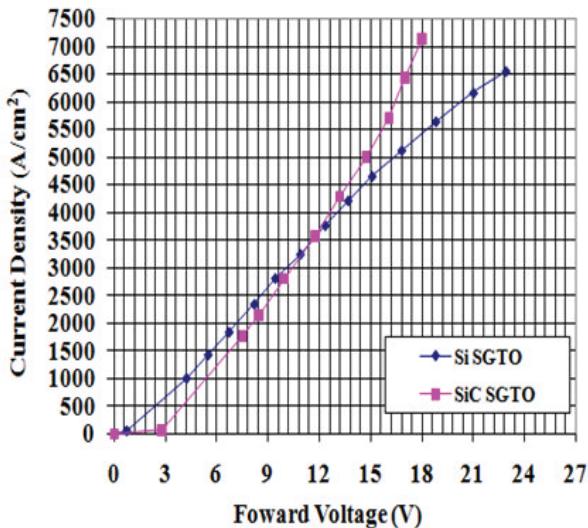


**Figure 10.** Anode current of module at 8 kA with a 170  $\mu$ s pulse-width. Overlay of pulse 1 and pulse 1000 [6].



**Figure 11.** Forward voltage drop of module at 8 kA peak current. Overlay of pulse 1 and pulse 1000 [6].

The narrow-pulse I-V curve comparison of a 3.5  $\text{cm}^2$  Si SGTO and the SiC module is displayed in Fig. 12. The Si and SiC I-V curves crossed at about 3.5  $\text{kA}/\text{cm}^2$  and the difference in the forward voltage drop ( $\Delta V=8 \text{ V}$ ) at 6.5  $\text{kA}/\text{cm}^2$  for both devices illustrates the superior capability of SiC at elevated current density levels. Improvements in the carrier lifetime should further enable larger SiC bipolar devices to be scalable and reliable.



**Figure 12.** Narrow-pulse I-V curve for Si and SiC SGTO with a crossover at about  $3.5 \text{ kA/cm}^2$

#### IV. SUMMARY

SiC SGTO modules were evaluated for pulse capability at pulse-widths of 1 ms and 170  $\mu\text{s}$ . The wide pulse evaluation of the SiC module resulted in a peak current of 5.0 kA with a 1 ms pulse-width, corresponding to an action of  $1.3 \times 10^4 \text{ A}^2\text{s}$ . and a current density of 3.5  $\text{kA/cm}^2$ . The module was reliably pulsed over 1000 times at 8 kA with a pulse-width of 170  $\mu\text{s}$ . This peak current level corresponds to a peak current density of 5.6  $\text{kA/cm}^2$  with a current rise time of 720  $\text{A}/\mu\text{s}$  and an action of  $5.0 \times 10^3 \text{ A}^2\text{s}$ . Both narrow and wide pulse output characteristics of SiC compared to Si highlights SiC high current density capability.

The results presented in this paper further support the development of larger area, higher voltage silicon carbide SGTOs to meet the Army's pulsed power switching needs.

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